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DESIGN OF INDUCTION COIL FOR OXYGEN FREE COPPER PRODUCTION

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Abstract: This paper deals with the design of an induction coil (IC) intended to be used for an oxygen free copper production. This coil differs in design because it should be placed in a vacuum or in a chamber filled with noble gas, such as Argon. The designed coil must be suitable for melting the copper in this environment. The coil design means, using the simulation of the melting process to determine the best, coil geometry, type of crucible, the required current, frequency, the consumed power, and time required for this process. These results will be used to determine the parameters of the induction furnace AC power source suitable for feeding such a melting process efficiently.

The Finite Element Analysis (FEA) intended to simulate the heating process to determine the best coil dimensions, and choosing the crucible. It is found that the best crucible used for the melting of copper is the carbon crucible.

Keywords: *Melting in vacuum, FEM, ANSYS, Induction Heating*

1. Introduction

Induction heating (IH) furnace for oxygen free copper production is a technique used for melting the copper (workpiece) by eddy currents induced directly inside the workpiece. The melting process and the casting of the melt must be done in a chamber filled with noble gas to obtain a pure dissolved copper free from impurities and avoiding oxidization due to the lack of Oxygen. Since there is no air turbulence inside this closed dark champer, this leads to neglecting the effect of emissivity and convection factors in the thermal analysis part of the (IC) design of this furnace.

Production of Oxygen-free copper is a very important activity to get rid of the scrap of this substance and turn it into an effective material. So, this project considered as one of the recycling activities that serve sustainability on one hand and clean the environment from such scrap on the other hand.

This type of copper is suitable to be used in production of electrical conductor, bus bars and any other conducting parts due to its low resistivity. The production of free oxygen by IH gives several advantages as compared with other furnaces, these are, fast start-up and fast heating, high production rates, calm operation, safe especially by using matching transformer, clean manufacturing environment, and requires low maintenance.

This work deals with the simulation and design of (IC) of the furnace used for this melting process. A simulation is done for the melting process of scrap copper using the electromagnetic-thermal coupled analysis adopting Finite Element Method (FEM) by using ANSYS computer package [1]. This step is the most important in the design of the furnace AC power supply because it will determine the most suitable dimensions and

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number of turns of the (IC), the air-gap, the crucible type and its dimensions, the quantity of the melted copper, the time elapsed of this process. the required magnitude of coil current and its frequency, and the consumed power in the specimen.

These results can be used to find the self-inductance of the induction coil in order to determine the tank capacitor, the required terminal voltage must be applied by the power supply, the required real current feeding the tank circuit from the furnace power supply. Hence, the power supply main parameters are determined.

This simulation leads also to optimize each of the above (IC) parameters, which is a complicated task because these parameters are inherently interdependent. This small induction furnace will show the required power per unit mass of copper. Hence, this will be the base to expect the capacity of high-power furnace.

2. The Simulation

It is already known that a 3-D FE analysis as a numerical method, using ANSYS computer package as a solver of partial differential equations. This method is considered to simulate the electromagnetic-thermal coupled analysis of the melting process [2] by solving Maxwell, and heat transfer equations [3]. This goal can only be achieved according to a computer program that follows the flow-chart shown in fig. (1).

A FE model including a principle (IC) of cylindrical shape with a crucible filled with copper scrap as a “specimen”, shown in Fig. 2.

The 3D analysis process takes a long processing time in the computer. To reduce this time, the symmetry feature around the center of the model, is considered and a 1/20 ratio of the cylindrical shape of the furnace, as shown in figures (3) is adopted. This maneuver makes it easy to rerun the analysis in a short processing time to obtain the most suitable parameters of the IC.

The first parameter studied in this approach is the choice of the crucible, because the product must be pure from impurities and oxidization. Crucible is a pot which is used to save metals for dissolving in a furnace.

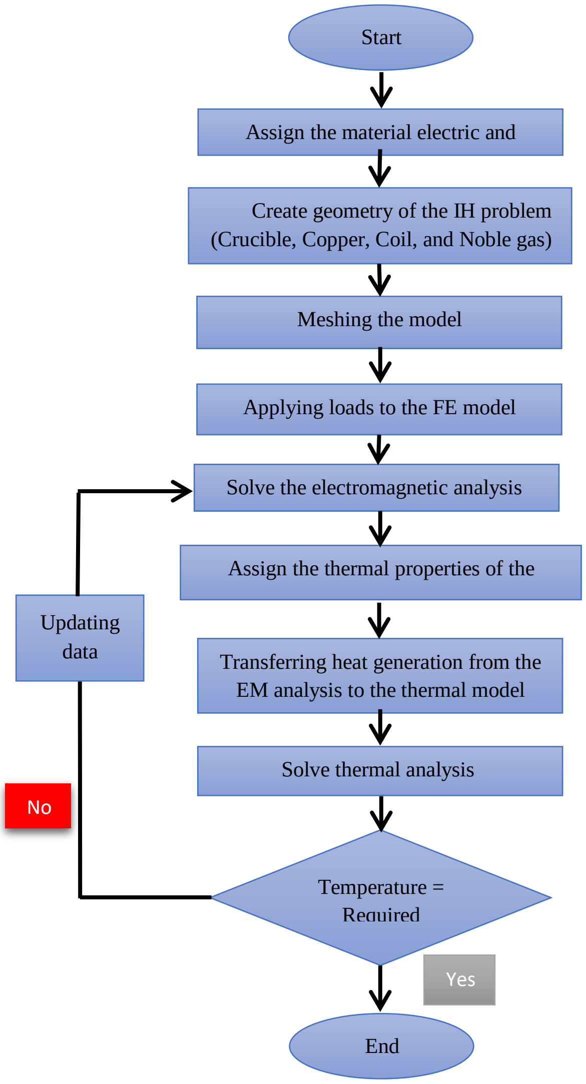

Figure 1. The flow-chart of the melting process

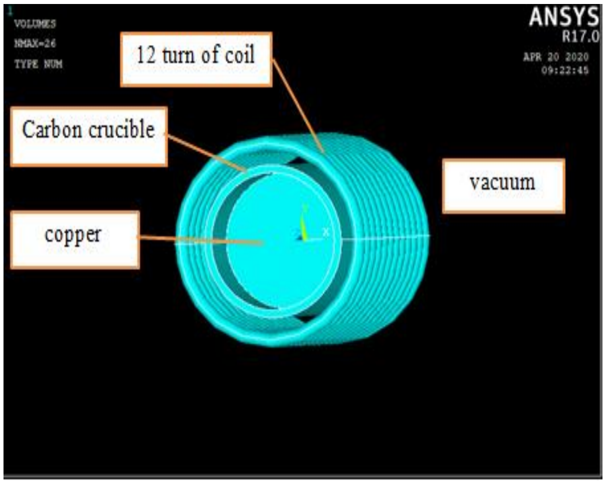

Figure 2. The principle shape of IC

Furnace crucibles are intended to withstand the highest temperatures experienced in the metal. The crucible ought to basically be made of materials with a lot higher melting point than that of the materials to be melted.

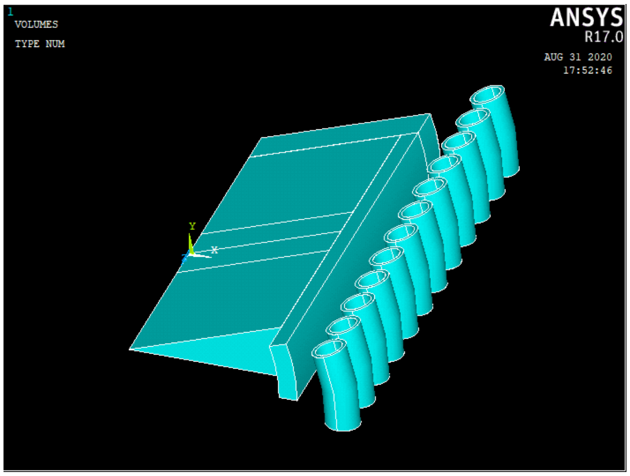

Figure 3. The $(1/20)$ section of the FE model

Some regular shapes for crucibles include "A" shape and bilge shape, Fig. (4 a. b). The "A” shape is studied in this research. This shape is easier to make than the shape of the bilge and therefore the cost is lower. A comparison in this research made between two "A” shape crucibles, one of them made of iron, while the other made of carbon.

Figure 4. a. "A" shape, b. bilge shape crucibles

The analysis done using these different crucibles as shown in Fig. (5). The carbon crucible is preferable due to the high melting point of the carbon and its parameters are not changed with temperature as that of iron sensitivity to Curie temperature. Also, to avoid scaling (flaking) in iron crucible.

The electromagnetic analysis for the IC reveals the eddy currents induced in the copper as shown in Fig. (6).

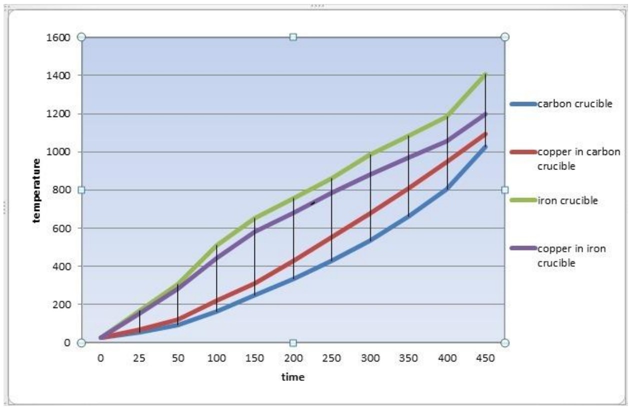

Figure. (5) temperatures increase vs. time of copper material in carbon and iron crucibles (J =11.24× $10^6 \mathrm{A \cdot m^{-2}}$, at f=75 kHz)

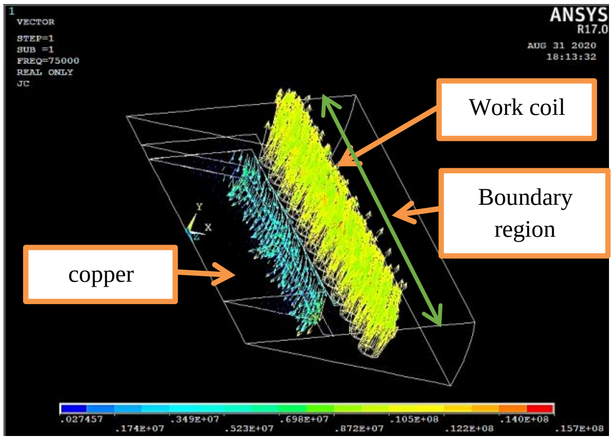

Figure 6. The induced eddy current in the copper to be melted and show the Skin effect.

The electromagnetic-thermal coupled analysis includes the calculation of the energy dissipated in each element at the end of each electromagnetic analysis as shown in Fig. (7). While the thermal transient analysis able to perform the contour plot of the temperature distribution inside the copper region and the crucible. Fig. (8) represent the temperature distribution of the carbon crucible at that point also.

3. The Design of the Induction Coil

As the analysis completed, then it becomes possible to choose the best dimensions of the induction coil. Since the crucible is chosen, then the minimum air-gap is the best choice, but the most effective number of turns must be determined. The melting process analysis repeated for different number of turns as shown in Fig. (9).

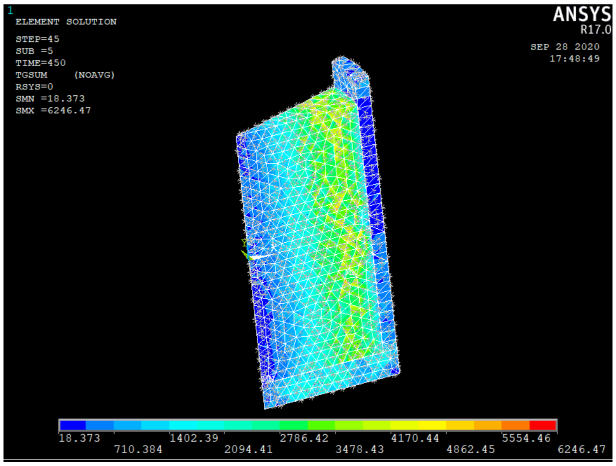

Figure 7. The dissipated energy due to eddy current in copper specimen

This result shows the 12 turns is the best choice and the corresponding current density in the induction coil is $J = 11.24 \times 10^6 \mathrm{A} \cdot \mathrm{m}^{-2}$, at melting time t= 450s. Fig. (10) represents a top view of the designed coil, taking into consideration that the coil length is 0.125m and the copper level of 0.1m height in the crucible of 0.12m height.

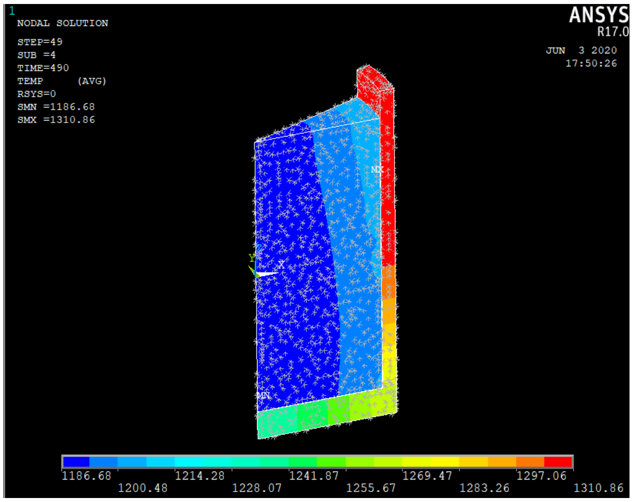

Figure 8. A temperature distribution of the copper using Carbon crucible.

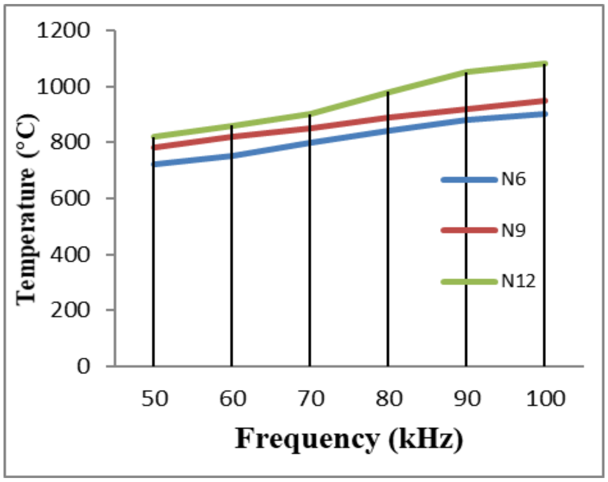

Figure 9. Effect of number of turns change on the maximum temperature using carbon crucible (J =11.24× $10^6 \mathrm{A} \cdot \mathrm{m}^{-2}$, t= 450s)

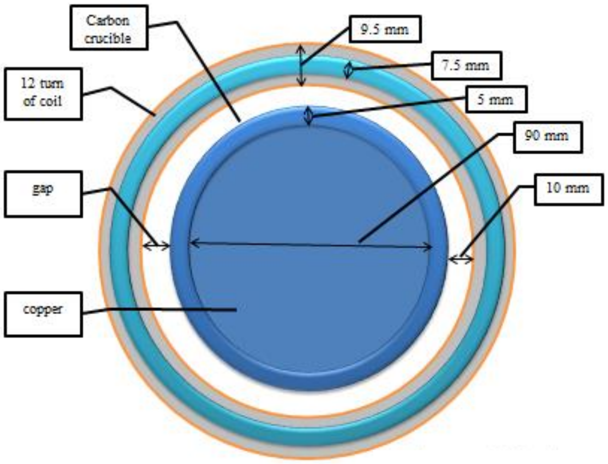

Figure 10. Top view of the induction coil with the designed dimensions

Many approaches are used to calculate the inductance of the induction coil, based on the accuracy. Wheeler's law is the most accurate one to measure the self-inductance of the air-cored, spiral form wound induction coil [3], given below:

$$L_c(\mu\mathrm{H}) = \frac{{r_c}^2 \times n_c^2}{0.2286\, r_c + 0.254\, l_c} \cdots (1)$$

Where,

$r_c \equiv$ the work coil radius, in m.

$l_c \equiv$ the height of the work coil in m.

$n_c \equiv$ the number of turns of the work coil.

$$L_c = \frac{0.06475^2 \times 12^2}{0.2286 \times\ 0.06475 + 0.254 \times\ 0.125}$$

$$L_c = 13\ \mu\mathrm{H}$$

To estimate the required power to be fed during the melting process, it is also possible to use the average specific heat of the copper ($395.7\ \mathrm{J} \cdot \mathrm{kg}^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}$), the mass per unit volume and the copper volume to be melted as a guide. Then the amount of energy needed can be calculated as follows:

$$\text{volume of copper} = \text{area of the base} \times \text{height}$$
$$= 4.5^2 \times \pi \times 10 = 636.17\mathrm{cm}^3$$
$$\text{mass of copper} = \text{volume} \times \text{density}$$
$$= 636.17 \times 8.96 = 5.7\mathrm{kgm}$$

Since the energy dissipated in both the copper and the crucible, then:

$$\text{energy 1}$$
$$= \text{mass of copper}$$
$$\times \text{average specific heat of copper} \times \Delta\mathrm{T}$$
$$= 5.7 \times 395.7 \times (1083 - 25) = 2386.3\mathrm{kJ}$$
$$\text{energy 2}$$
$$= \text{mass of carbon crucible}$$
$$\times \text{average specific heat of carbon crucible}$$
$$\times \Delta\mathrm{T} = 0.5 \times 706.9 \times (1083 - 25) = 373.9\mathrm{kJ}$$
$$\text{total energy} = \text{energy 1} + \text{energy 2}$$
$$= 2386.3 + 373.9 = 2760.2\mathrm{kJ}$$

The power required to melt 5.7kgm of copper can be calculated by dividing the total energy by the time taken for the melting process, then:

$$\text{power}(P_{real}) = \text{total energy/time}$$
$$= 2760.2/450 = 6.1\mathrm{kw}$$

Since the induction coil is connected in parallel with resonant capacitor to form a tank circuit, the tank capacitor C_o determined as follows:

$$f_{\mathrm{o}} = \frac{1}{2\pi\sqrt{L_c C_o}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$C_o = \frac{1}{4\pi^2 {f_o}^2 L_c} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

$$C_o = \frac{1}{4\pi^2 \times 75000^2 \times 13 \times 10^{-6}} = 0.346\ \mu\mathrm{F}$$

To determine the required voltage that must be supplied by the voltage source feeding this process, the tank circuit behavior have to be comprehended.

The output voltage from the power supply is a square wave tuned to operate at frequency exactly equal to that of the resonance tank circuit. The well-known frequency spectrum of this waveform is composed of a wide band of harmonics.

The tank circuit is considered approximately as a short circuit path of all the square wave harmonics except the fundamental one. Hence, the fundamental will appear across the tank circuit as a voltage of sinusoidal waveform.

Then, this voltage appears across the tank capacitor. Since, the current passing through the capacitor is the same as that of the induction coil current, then the magnitude of this voltage can be calculated as:

$$V_s = I_c \times X_{C_o} \cdots\cdots\cdots\cdots\cdots (4)$$

$$X_{C_o} = \frac{1}{2\pi f_o C_o} \cdots\cdots\cdots\cdots\cdots (5)$$

$$X_{C_o} = \frac{1}{2\pi \times 75 \times 10^3 \times 0.346 \times 10^{-6}}$$
$$= 6.133\Omega$$

$$I_c = J \times A_c$$

Since, the coil conductor is a hollow copper tube of external radius ($r_{ext} = 4.75\mathrm{mm}$) and of internal radius ($r_{int} = 3.75\mathrm{mm}$), then the resultant area of the conductor (A_c) is:

$$A_c = \pi r_{ext}^2 - \pi r_{int}^2$$
$$A_c = \pi(4.75^2 - 3.75^2) \times 10^{-6}$$
$$= 26.7 \times 10^{-6}\mathrm{m}$$
$$I_C = 11.24 \times 10^6 \times 26.7 \times 10^{-6} = 300.1\mathrm{A}$$
$$\therefore V_s = 6.133 \times 300.1 = 1840.8\mathrm{V}$$

Hence, the real current that must be supplied by the furnace power supply will be:

$$I_s = \frac{P_{real}}{V_s} = \frac{6133.77}{1840.8} = 3.332\text{A}$$

The equivalent resistance connected in series with the induction coil self-inductance is:

$$R_{series} = \frac{P_{real}}{I_c^2} = \frac{6133.77}{300.1^2} = 0.0681\Omega$$

4. Discussion and Conclusion

The obtained results from this work leads to use the carbon crucible to melt the oxygen free copper. Also, the numerical analysis leads to the equivalent circuit of the induction coil. The final equivalent circuit of the induction coil with the expected power supply is shown in fig. 11.

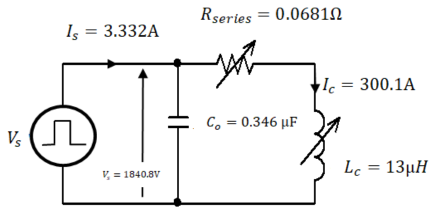

Figure 11. Equivalent circuit of the induction coil

The previous analysis leads to conclude that the induction coil current more than that feeds the tank circuit. This ratio represents the quality factor

$$Q = \left(I_{imag}/I_{real}\right) = \left(I_c/I_s\right)$$
$$Q = (300.1/3.332) = 99.1$$

This ratio explains the reason of using the tank parallel circuit furnace in high power applications.

The theoretical results obtained in the simulation cannot be achieved practically. This is due to the fact that the high frequency, high current circuit is very sensitive to connections geometry. Also, the component exact values are not available commercially like the tank capacitance. Hence, the achieved results lead to understand the behavior of the system. The verification of this design approach can be approved when the implementation of this furnace finished in near future.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

5. References

1. Isam Mahmood Abdulbaqi, "Analysis of Induction Furnace using FEM Electromagnetic-Thermal Coupled Approach", Ph.D. Thesis, Al-Rasheed College of Engineering and Science/ UOT, Baghdad, Iraq, January 2006.
2. Mohammad Hameed Khazaal, "Design, Simulation and Implementation of a High Frequency Power Source Feeding an Induction Furnace", Ph.D. Thesis, Collage of Engineering /University of Basrah, Iraq, March 2016.
3. Daniel Fleisch,"A Student's Guide to Maxwell's Equations", Cambridge University Press, 2008.
4. Valery Rudnev, Don Loveless and Raymond Cook, "Handbook of Induction Heating", Marcel Dekker, Inc. New York, USA, pp.99-116, 2003.
5. S. Zinn and S. L. Semiatin, "Elements of Induction Heating: Design, Control, and Applications", ASM International and (EPRI) Electronic Power Research Institute, pp.9-15, 1988.
6. Richard E. Haimbaugh, "Practical Induction Heat Treating", ASM International, 2001.
7. Raymond A. Higgins, "Engineering Metallurgy Part1 Applied Physical Metallurgy", Sixth Edition, A member of the Hodder Headline Group, 1993.
8. Reza Abbaschian, Lara Abbaschian, Robert E Reed-Hill, "Physical Metallurgy", Fourth Edition, United States of America, 2008.

9. Ramón Bargallo, "Finite Elements for Electrical Engineering", EUETIB-UPC, 2006.
10. Mark W. Kennedy, Shahid Akhtar, Jon Arne Bakken, and Ragnhild E. Aune, "Empirical Verification of a Short-Coil Correction Factor", IEEE Trans. on Industrial Electronics, vol. 61, no. 5, May 2014.
11. Mitch Tilbury, "The Ultimate Tesla Coil Design and Construction Guide", McGraw-Hill, pp.23-26, 2008.